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EXTREME HOST GALAXY GROWTH IN POWERFUL EARLY-EPOCH RADIO GALAXIES

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ABSTRACT

During the first half of the universe’s life, a heyday of star formation must have occurred because many massive galaxies are in place after that epoch in cosmic history. Our observations with the revolutionary *Herschel Space Observatory* reveal vigorous optically obscured star formation in the ultra-massive hosts of many powerful high-redshift 3C quasars and radio galaxies. This symbiotic occurrence of star formation and black hole driven activity is in marked contrast to recent results dealing with *Herschel* observations of X-ray-selected active galaxies. Three archetypal radio galaxies at redshifts 1.132, 1.575, and 2.474 are presented here, with inferred star formation rates of hundreds of solar masses per year. A series of spectacular coeval active galactic nucleus/starburst events may have formed these ultra-massive galaxies and their massive central black holes during their relatively short lifetimes.

Key words: galaxies: formation – galaxies: high-redshift – galaxies: starburst – infrared: galaxies

1. INTRODUCTION

The most massive galaxies known have stellar masses $\sim 5 \times 10^{11} M_{\odot}$, and the fact that they already exist at early epochs (Fontana et al. 2006) implies that they must have formed rapidly (Daddi et al. 2005), within just a few gigayears. They are expected to host supermassive black holes (Häring & Rix 2004) which have periods of active accretion (De Breuck et al. 2010). A symbiotic occurrence of modest star formation and accretion activity has been inferred in the high-mass host galaxies of intermediate-redshift X-ray-selected active galactic nuclei (AGNs; Lutz et al. 2010). Additional interest in the details of the symbiosis in radio-loud AGNs is moreover generated by the proposed negative AGN feedback (e.g., Bower et al. 2006). Here we quantitatively address star formation and black hole build-up in the most massive galaxies hosting radio-loud AGNs, during their time of formation.

Powerful high-redshift radio galaxies are ideal tracers of the extreme form of starburst–AGN symbiosis for several reasons. First, their central black holes are being fed at a high rate, and hence are rapidly growing. Second, their large extended radio sources allow an unambiguous quantification of the accretion power, from the huge radio luminosities; moreover, their radio morphological properties permit an estimate of the duration of the AGN and possibly coeval star formation episodes. Third, the presence of large reservoirs of molecular gas, the necessary fuel for star formation, has been inferred (Solomon & Vanden Bout 2005) from (sub)-millimeter spectroscopy in some radio galaxies (but not in all). Quantification of the ongoing star formation is provided through far-infrared (FIR) observations, since dust absorbs the radiation of the young stars and re-emits it at FIR wavelengths. From rest-frame submillimeter (submm) photometry (Benford et al. 1999; Reuland et al. 2004) and mid-infrared spectral energy distributions (SEDs; Seymour et al. 2008), it was suspected that some powerful high-redshift radio galaxies might be experiencing phases of copious (dust obscured) star formation. The implications from the SED measurements, however, were uncertain: the amount of cool dust reradiating the emission of the newly formed stars was not well constrained, as data from the rest-frame far-infrared regions and the Rayleigh–Jeans tails were lacking.

The *Herschel Space Observatory*⁵ (Pilbratt et al. 2010) provides full measurement of IR-submm SEDs at unprecedented sensitivity. This Letter presents breakthrough results on a sample of 70 radio-loud, high-redshift AGNs, namely quasars and radio galaxies from the 3C and 4C catalogs. With $P_{1.4\text{ GHz}} \sim 10^{27.5} \text{ W Hz}^{-1}$, these AGNs contain the most powerful accreting black holes. Inspection of our sample measurements shows FIR detection fractions of roughly two in three objects, at both $160 \mu\text{m}$ and $250 \mu\text{m}$ (from the *Herschel* PACS and SPIRE instruments, respectively). Stressing that the non-detected objects are probably just below the sensitivity limit, we focus here on three archetypal objects, reporting on their spectacular ongoing star formation.

3C 368 (Best et al. 1997, 1998a, 1998b; Chambers & Charlott 1990; Djorgovski et al. 1987), 3C 68.2 (Best et al. 1997, 1998b; Chambers & Charlott 1990; Djorgovski et al. 1988), and 3C 257 (Van Breugel et al. 1998), at redshifts $z = 1.132, 1.575$, and 2.474 , respectively, are archetypal protogalaxies with well-documented properties. 3C 257 is the highest redshift object in the complete 3CR sample (Spinrad et al. 1985). The first studies of 3C 68.2 and 3C 368 in the mid and late 1980s, and their identification as protogalaxies, marked the birth of the K - z -diagram (Lilly & Longair 1984) and the beginning of extensive observations of their massive hosts in a cosmological context (Spinrad 1986). The presence of a luminous QSO—a Type 1 AGN, obscured from direct view behind a toroidal circumnuclear dust configuration—was proven in the case of 3C 257 from X-ray data (Derry et al. 2003); similarly the two other objects reveal obscured QSOs in our as yet unpublished *Chandra* data.

2. OBSERVATIONS AND RESULTS

Photometric observations of 3C 368, 3C 68.2, and 3C 257 were carried out as part of a *Herschel* Guaranteed Time program—see Table 1. The PACS scan-map mode was employed with cross scans in the blue ($70 \mu\text{m}$) and the red ($160 \mu\text{m}$) bands, yielding angular resolutions of, respectively, $5''$ and $11''$.

⁵ *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA

Table 1
Observations and Measured Flux Densities

Object	R.A.(J2000)	Decl.(J2000)	Obs. Date	Obs. Band	Integr. Time	Flux Density (mJy)
3C 368	18 ^h 05 ^m 06 ^s .36	+11°01′32″.5	2011 Mar 22	70 μ m	160 s	30.0 \pm 2.0
			2011 Mar 22	160 μ m	160 s	56.0 \pm 3.0
			2011 Mar 28	250 μ m	111 s	31.1 \pm 7.0
			2011 Mar 28	350 μ m	111 s	20.1 \pm 6.6
			2011 Mar 28	500 μ m	111 s	<21.0
3C 68.2	02 ^h 34 ^m 23 ^s .86	+31°34′17″.5	2011 Jul 10	70 μ m	160 s	27.0 \pm 6.0
			2011 Jul 10	160 μ m	160 s	40.0 \pm 7.0
			2011 Jul 31	250 μ m	111 s	28.7 \pm 7.1
			2011 Jul 31	350 μ m	111 s	29.6 \pm 7.4
			2011 Jul 31	500 μ m	111 s	19.7 \pm 7.0
3C 257	11 ^h 23 ^m 09 ^s .17	+05°30′19″.5	2011 Jun 1	70 μ m	640 s	11.6 \pm 1.0
			2011 Jun 1	160 μ m	640 s	16.0 \pm 1.7
			2010 Nov 23	250 μ m	296 s	22.8 \pm 4.9
			2010 Nov 23	350 μ m	296 s	20.1 \pm 5.7
			2010 Nov 23	500 μ m	296 s	20.4 \pm 6.8

Notes. *Herschel* observations using the PACS and SPIRE instruments yielded photometric data in five bands. The 1σ errors combine the measurement noise and the background noise.

Data reduction was performed within HIPE (Ott 2010) following standard procedures for deep field observations, including source masking and high-pass filtering. Both scan directions were processed individually and then mosaicked to yield the final map. Aperture photometry (including appropriate aperture corrections) of the sources at the known radio core positions was carried out to measure source flux densities. Photometric uncertainties were determined by measuring the flux in several apertures on empty parts of the background. The SPIRE small map mode was employed in the 250 μ m (18'' resolution), 350 μ m (25''), and 500 μ m (36'') bands. Data processing followed standard procedures for small map data within HIPE. The photometry was performed utilizing a SPIRE source extractor also implemented in HIPE (Savage & Oliver 2007). The uncertainties of the SPIRE photometry are dominated by confusion noise. Combining the *Herschel* data with our existing (Haas et al. 2008) *Spitzer* mid-infrared photometry, we were able to trace our science targets as well as other objects in the fields over two decades in wavelength. With this approach, we ensure proper identifications while avoiding source confusion. Supplementing our *Herschel* and *Spitzer* data with published photometry, we obtain the complete optical–IR–submm SEDs. To extract physical parameters, we fitted the data with three components representing the typical constituents of a radio galaxy SED. In practice, we started with the AGN-powered warm dust emission by cycling through a library of torus models covering a wide range in the relevant parameter space (Hönig & Kishimoto 2010). For each torus model (using edge-on inclinations of 60°, 75°, or 90°) we added a blackbody in the optical–NIR for emission from the host galaxy stars⁶ as well as a modified blackbody of variable temperature (gray-body model with β fixed at 1.6) in the FIR/submm to account for possible excess emission due to star formation. Figure 1 shows for each source the combination of one of the torus models, scaling for all components, and FIR dust temperature which minimizes the chi-square overall, i.e., the best-fitting model. Errors on the derived physical parameters were determined from the distribution of these parameter values for the

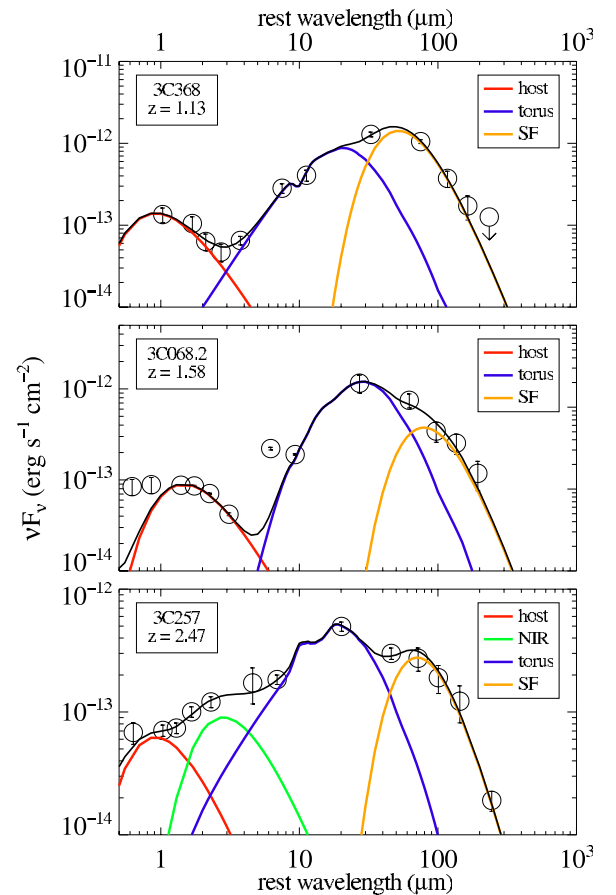


Figure 1. Infrared-submm spectral energy distributions. The infrared-submm SEDs of 3C 368, 3C 68.2, and 3C 257 are shown, with the best-fitting, multi-component model superposed: stellar radiation (red), torus radiation (blue), and cool dust radiation (yellow). 3C 257 requires an extra hot dust component (green)—see the main text. The mismatch at 16 μ m for 3C 68.2 is possibly due to luminous polycyclic aromatic hydrocarbon emission. The error bars reflect $\pm 1\sigma$ errors.

⁶ 3C 257 required the addition of an extra blackbody of ~ 1300 K. Such a component, which is generally identified with hot dust close to the sublimation temperature, is often observed in Type 1 AGNs but has not been seen in Type 2 AGNs so far. Inclusion or exclusion of this hot dust component does not affect the forthcoming conclusions.

range of model combinations consistent with the data. Since radio galaxy jets have large inclinations, radio core emission is relativistically de-boosted rather than boosted as in quasars. Core radio data (Best et al. 1997, 1998a; Van Breugel et al. 1998)

Table 2
AGN and Star Formation Luminosities

Object	Redshift	T_{cool} (K)	L_{AGN} (erg s^{-1})	L_{SF} (erg s^{-1})	L_{SF} ($10^{12} L_{\odot}$)	SFR ($M_{\odot} \text{ yr}^{-1}$)	Radio Size (kpc)	M_{host} (M_{\odot})	M_{host} /Radio Refs.
3C 368	1.132	53 ± 1	$(7.3 \pm 3.5) \times 10^{45}$	$(1.4 \pm 0.04) \times 10^{46}$	3.5 ± 0.1	610	80	$10^{11.6}$	Best et al. (1998a, 1998b)
3C 68.2	1.575	36 ± 3	$(3.3 \pm 1.0) \times 10^{46}$	$(8.6 \pm 0.8) \times 10^{45}$	2.2 ± 0.2	390	190	$10^{11.7}$	Best et al. (1997, 1998b)
3C 257	2.474	37 ± 3	$(4.1 \pm 2.0) \times 10^{46}$	$(1.7 \pm 0.1) \times 10^{46}$	4.4 ± 0.3	770	95	$<10^{11.7}$	De Breuck et al. (2010); Van Breugel et al. (1998)

Notes. The inferred AGNs and star formation luminosities for the three high-redshift radio galaxies are listed, as well as their (projected) radio source sizes and host galaxy masses, taken from the literature (with references). The 1σ errors were determined from the distribution of the 10 best model combination sets.

indeed show that any non-thermal contribution to the submm emission is negligible. While the SPIRE beam also encloses the radio source hot spots, their contribution is negligible since even the total integrated radio SED underpredicts the FIR/submm by a large margin. As Figure 1 shows, substantial cool dust emission is called for by the SED gray bodies, with temperatures of 53 K, 36 K, and 37 K, for 3C 368, 3C 68.2, and 3C 257, respectively. Using standard cosmology ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\Lambda} = 0.73$, $\Omega_m = 0.27$), we compute source intrinsic properties, which are listed in Table 2. The listed L_{AGN} -values originate from the torus modeling: They represent the (accretion) luminosities required to power the fitted torus emission. The L_{SF} -values were determined by integrating the fitted FIR gray bodies between $8 \mu\text{m}$ and $1000 \mu\text{m}$.

3. DISCUSSION

In analogy with other studies (Benford et al. 1999; Hatziminaoglou et al. 2010) we attribute the torus heating, i.e., the warm dust component, to the obscured AGNs: Their luminosities are $\sim 10^{46} \text{ erg s}^{-1}$, confirming the luminous active accretion in these radio-loud Type 2 AGNs, which is consistent with the unification scenario (Barthel 1989; Derry et al. 2003; Haas et al. 2004; Ogle et al. 2006). Attributing the cool dust emission to star formation, we determine luminosities which are comparable to the AGN luminosities (Table 2), all in excess of $10^{12} L_{\odot}$. Using standard conversions (Kennicutt 1998), the star formation rate (SFR) values are 610, 390, and $770 M_{\odot} \text{ yr}^{-1}$, for 3C 368, 3C 68.2, and 3C 257, respectively. Hence, all three high- z radio galaxies are prodigious star formers.⁷ Four points are noteworthy: (1) when comparing the SFRs with values inferred from UV/optical data (Chambers & Charlot 1990) we conclude that most of the star formation in these three objects is strongly obscured in that band, (2) as judged from their radio sizes (this point will also return later), these are mature objects rather than young AGNs in a transition phase from dust obscured infrared galaxies to AGNs, (3) 3C 68.2 and 3C 257 have cool dust temperatures in the range of those measured for distant submm galaxies (Magnelli et al. 2012), and (4) as judged from the detection statistics ($\sim 70\%$), many (if not all) of our sample objects must have optically obscured star formation of comparable strength, i.e., SFRs of hundreds of $M_{\odot} \text{ yr}^{-1}$. The high star formation luminosities for these high- z radio galaxies are consistent with results from deep field *Herschel* surveys targeting a mix of radio-quiet AGN types over a large redshift range out to $z \sim 3$ (Hatziminaoglou et al. 2010; Elbaz et al. 2010; Mullaney et al. 2012b) and with results from $z > 4$ QSO studies (Leipski et al. 2010), but our detection fraction is higher.

Our observations indicate that many distant powerful radio galaxies display star formation at a level comparable to ultra-luminous infrared galaxies (ULIRGs) which is coeval to their black hole activity. That conclusion, together with the above-mentioned results of *Herschel* studies dealing with powerful radio-quiet AGNs, is in marked contrast with the conclusion (Page et al. 2012) for X-ray-selected $1 < z < 3$ (radio-quiet) AGNs in the CDF-N, namely, that ultra-luminous starburst activity is not seen in the most powerful AGN. While detailed comparison of these conflicting results is beyond the scope of this Letter we point out two possible explanations. First, the hosts of the CDF-N AGNs are of lower stellar mass than the radio source hosts. We stress that distant 3C and 4C objects (of which only of order 10^2 are known) represent the highest peaks in the galaxy mass distribution. In fact, our observations are in broad agreement with the extrapolated cosmologically evolving specific SFR, sSFR, in the hosts of luminous AGNs (and star-forming galaxies) recently established by Mullaney et al. (2012b). A (puzzling) inverse correlation between AGN X-ray strength and host galaxy mass would be required to explain the Page et al. (2012) results within the just mentioned sSFR behavior in combination with our findings for radio-loud AGNs. Second, radio-selected AGNs—selected using radio lobe luminosity, which is an isotropic property—represent a cleaner, more complete AGN subsample than do X-ray-selected AGNs: The latter may lack the most obscured sources. The X-ray luminosities reported by Page et al. (2012) are uncorrected for obscuration, who estimate the effect is small. X-ray observations for the 3C sources reported here indicate observed luminosities, assuming a standard power-law spectrum with $\Gamma = 1.9$, of about $3 \times 10^{43} \text{ erg s}^{-1}$, $4 \times 10^{43} \text{ erg s}^{-1}$ (B. J. Wilkes et al. 2012, in preparation), and $1.5 \times 10^{44} \text{ erg s}^{-1}$ (Derry et al. 2003) for 3C 68.2, 3C 368, and 3C 257, respectively, comparable with sources in the Page et al. (2012) sample. It is well known that low signal-to-noise (S/N) X-ray data provide poor estimates of obscuration and so result in luminosities uncertain by 1–2 dex (Cappi et al. 2006; Wilkes et al. 2005). Indeed, for all three 3C sources reported here (radio galaxies), the X-ray data indicate significant obscuration with estimated $N_{\text{H}} \sim 10^{23}–10^{24}$, yielding estimated intrinsic, hard-band X-ray luminosities of $\sim 10^{45} \text{ erg s}^{-1}$ for 3C 68.2 and 3C 368 (B. J. Wilkes et al. 2012, in preparation) and $9 \times 10^{44} \text{ erg s}^{-1}$ for 3C 257 (2–10 keV; Derry et al. 2003). The low S/N of the X-ray data combined with the likely presence of additional, unobscured, radio-jet-linked emission (responsible for the typically $3\times$ brighter X-ray luminosities in radio-loud quasars; Zamorani et al. 1981) make it likely that the N_{H} and intrinsic X-ray luminosity for these three 3C sources remain underestimated. Although X-ray emission in radio-quiet AGNs is less complex and may be of somewhat lower luminosity, the stronger bias against highly obscured sources and the difficulty in detecting absorption in the fainter X-ray sources, which are those most

⁷ For comparison, we performed the same decomposition for the host of the powerful low-redshift radio galaxy Cygnus A (3C 405), using published (Haas et al. 2004) SED data, finding considerably lower values: $L_{\text{AGN}} = 8.2 \times 10^{44} \text{ erg s}^{-1}$ and $L_{\text{SF}} = 1.5 \times 10^{11} L_{\odot}$ (SFR $26 M_{\odot} \text{ yr}^{-1}$).

likely to be obscured (Kim et al. 2007), is very likely to result in significantly underestimated X-ray luminosities in the Page et al. X-ray-selected sample. The fact that a higher incidence of X-ray absorption in those sources with 250 μm detections is also reported strengthens this possibility and so questions their main conclusion: that 250 μm emission is undetected, indicating that SF is quenched, in the highest luminosity, $L_X \gtrsim 10^{44} \text{ erg s}^{-1}$, active galaxies in their sample. Careful examination of the true nature of the high- z X-ray AGNs is required to back up the proposed negative feedback; such feedback is definitely not observed in the radio-loud(est) AGNs. While the duration of the vigorous star formation phase could be longer than the radio-loud activity episode, with the star formation starting earlier than and possibly eventually being quenched by the AGN (analysis of our full sample of young, mature, and old radio sources will address that issue), based on our observations, there is a substantial symbiotic period.

In contrast to other AGNs, radio galaxies—with their extended radio structure at high inclination—offer the unique possibility of estimating the age of the activity episode from the linear size of the structure, adopting a typical (Best et al. 1995) source expansion speed of 10%–20% of the speed of light. The average duration of such an episode follows from the maximum size of radio galaxies at the relevant cosmic epoch. Then 3C 68.2, measuring $\sim 190 \text{ kpc}$, has a large dimension, implying its AGN phase has an age of several million years, while the sizes of 3C 368 and 3C 257 indicate that they are somewhat younger. Focusing on 3C 68.2, and adopting an AGN age of 5 Myr, a symbiotic star formation phase at the inferred SFR of $\sim 500 M_\odot \text{ yr}^{-1}$, assuming it to be constant, would yield $\sim 2.5 \times 10^9 M_\odot$. The actual figure could be larger if the star formation commenced before the AGN phase. The host mass of 3C 68.2, $5 \times 10^{11} M_\odot$ (Best et al. 1998b), can be formed through ~ 200 such gas accretion phases, for which there is sufficient time given the age of the universe at that redshift of 4 Gyr. The ~ 200 associated AGN phases will last a total time of $\sim 10^9 \text{ yr}$, during which a massive central black hole of $\sim 1 \times 10^9 M_\odot$ must accrete (Häring & Rix 2004). The implied average black hole fuel consumption of $1 M_\odot \text{ yr}^{-1}$ yields an energy output $\sim \eta \dot{m} c^2$ which for a typical accretion efficiency $\eta = 0.1$ equals $5 \times 10^{45} \text{ erg s}^{-1}$ —about a factor seven below the observed AGN luminosity of 3C 68.2. An essential element in this discussion is the assumption that the growth of the central black hole during AGN episodes is in phase with the build-up of its host galaxy. We cannot exclude the possibility of a more energetic star-forming phase (for instance at $\text{SFR} \sim 10^4 M_\odot \text{ yr}^{-1}$), but such SFRs remain to be observed in high-redshift radio galaxies. However, if the star-forming phase lasts about a factor of 10 longer than the symbiotic phase, then ~ 20 such events are needed to build up the massive galaxy. In that case, the mass consumption required to build its black hole during the ~ 20 AGN episodes would be in agreement with the measured AGN luminosity. Other forms of symbiotic occurrences can also be envisaged, including pure AGN phases not linked to coeval starbursts and the direct capture of stars through galaxy–galaxy merging. Whereas low-redshift ULIRGs are believed to originate from major mergers, high-redshift ULIRGs in the form of submm galaxies might have formed through cold gas accretion (Davé et al. 2010); the same has been postulated for high-redshift AGNs (Bournaud et al. 2011). Even at their extreme stellar masses, our 3C hosts obey the $s\text{SFR}(z)$ behavior for non-AGNs and X-ray AGNs (Mullaney et al. 2012b). However, their X-ray luminosities are higher, by orders of magnitudes;

moreover, they are radio loud. They may well mark the rare, most extreme examples of the universal accretion to SFR ratio postulated by Mullaney et al. (2012a). Following these authors, we contend that the full symbiosis whereby a cold gas inflow driven, vigorous star formation episode leads into (and may be quenched by) an energetic AGN phase, offers an attractive scenario for the reason for a common fuel supply, building up both black hole and stellar mass.

4. CONCLUSIONS

Following implications from submm emission, mid-IR spectra, and $\text{Ly}\alpha$ emission, we now know unambiguously that a substantial fraction of the hosts of high-redshift radio galaxies are dust and gas rich, undergoing one of likely many phases of copious star formation. Energetically speaking, they are comparable to ULIRGs. Our study shows accretion and star formation activity simultaneously at work in the most massive early-epoch galaxies, building these galaxies and their central black holes, forcefully and effectively. It will be important to extend the investigations to radio-loud AGNs hosted by less massive galaxies. Radio-loud activity phases must play an important role in galaxy formation.

The *Herschel* spacecraft was designed, built, tested, and launched under a contract to ESA, managed by the *Herschel*/Planck Project team, by an industrial consortium under the overall responsibility of the prime contractor Thales Alenia Space (Cannes), and including Astrium (Friedrichshafen) responsible for the payload module and for system testing at spacecraft level, Thales Alenia Space (Turin) responsible for the service module, and Astrium (Toulouse) responsible for the telescope, with in excess of a hundred subcontractors. HCSS/HSpot/HIPE is a joint development by the *Herschel* Science Ground Segment Consortium, consisting of ESA, the NASA *Herschel* Science Center, and the HIFI, PACS, and SPIRE consortia. We acknowledge the support and interest of the full Guaranteed Time Proposal team, of Dutch liaison astronomer Max Avruch, of colleague Karina Caputi, and the comments of an expert referee.

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